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RADIALLY VARYING AND AZIMUTHALLY ASYMMETRIC OPTICAL WAVEGUIDE FIBER

BACKGROUND OF THE INVENTION

This application is based upon the provisional application S.N. 60/099,535, filed 9/9/98, which we claim as the priority date of this application.

The invention relates to an optical waveguide fiber and a method of making a waveguide fiber, having a refractive index profile which varies in both the radial and azimuthal directions. The additional flexibility afforded by the azimuthal variation provides for index profile designs which meet a larger number of waveguide fiber performance requirements than is possible using refractive index variation in only the radial coordinate direction.

Recent development of waveguide fibers having refractive index profiles which vary in the radial direction has shown that particular properties of the waveguide can be optimized by adjusting this profile. Varying the refractive index profile in a more general way than, for example, a simple step, allows one to select the value of one or more waveguide properties without sacrificing a base set of properties including attenuation, strength, or bend resistance.

In addition, certain azimuthal asymmetric core refractive index profiles, such as those having elliptical, triangular, or square core geometry have been shown to provide useful waveguide properties such as preservation or mixing of the polarization modes.

It is expected, therefore, that core refractive index profiles which vary in both the azimuthal and radial direction will offer the opportunity to fabricate waveguides having new or improved properties for use in telecommunication, signal processing, or sensor systems.

In U. S. patent 3,909,110, Marcuse, ('110 patent) an azimuthally asymmetric core of a multimode waveguide is described. A calculation in the '110 patent indicates that periodic variations in index in both the radial and azimuthal directions would cause mode coupling, thereby increasing bandwidth, while limiting losses due to coupling to radiation modes. The concept was not extended to include single mode waveguides. Also the scope of the '110 patent is quite limited in that it refers only to sinusoidal azimuthal variations.

In describing the present azimuthally and radially asymmetric core, the concept of core sectors is introduced. A core sector is simply a portion of the core which is bounded by a locus of points of a first and a second radius which form an annular region in the waveguide. Each of the radii are different one from another and are less than or equal to the core radius. The remaining boundaries of a sector are two planes oriented at an angle with respect to each other and each containing the waveguide fiber centerline. A change in refractive index along a line within a sector means the refractive index is different between at least two points along the line.

DEFINITIONS

The following definitions are in accord with common usage in the art.

- A segmented core is a core which has a particular refractive index profile over a pre-selected radius segment. A particular segment has a first and a last refractive index point. The radius from the waveguide centerline to the location of this first refractive index point is the inner radius of the core region or segment. Likewise, the radius from the waveguide centerline to the location of the last refractive index point is the outer radius of the core segment.
- The relative index, Δ, is defined by the equation, $\Delta = (n_1^2 - n_2^2)/2n_1^2$, where n_1

is the maximum refractive index of the index profile segment 1, and n_2 is a reference refractive index which is taken to be, in this application, the minimum refractive index of the clad layer. The term Δ %, which is 100 X Δ, is used in the art.

- The term refractive index profile or simply index profile is the relation between Δ % or refractive index and radius over a selected portion of the core. The term α-profile refers to a refractive index profile which follows the equation,

$n(r) = n_0 (1- \Delta[r/a]^{\alpha})$ where r is core radius, Δ is defined above, a is the last point in the profile, r is chosen to be zero at the first point of the profile, and α is an exponent which defines the profile shape. Other index profiles include a step index, a trapezoidal index and a rounded step index, in which the rounding is typically due to dopant diffusion in regions of rapid refractive index change.

SUMMARY OF THE INVENTION

In a first aspect of the invention, a single mode waveguide has a core having at least one sector. The refractive index of at least one point within the sector is different from that of at least one point outside the sector. In the case where the sector is exactly half the core, the choice of what constitutes a point inside the sector can be chosen arbitrarily without any loss of precision of definition of the profile. The core refractive index profile changes along at least a portion of one radius to provide radial asymmetry. At a pre-selected radius the core refractive index within the sector is different from that outside the sector to provide azimuthal asymmetry.

In one embodiment, the overall core has cylindrical symmetry and thus is conveniently described in cylindrical coordinates, radius r, azimuth angle φ, and centerline height z. The pre-selected radius portion, Δr along which the refractive index changes is in the range $0 < \Delta r \leq r_o$, where r_o is the core radius. The pre-selected radius at which the refractive index is different for at least two different choices of azimuth angle is within this same range.

In another embodiment the pre-selected radius portion is a segment defined as $\Delta r = r_2 - r_1$, where, $0 \leq r_1 < r_2$ and $r_2 < r_o$.

In yet another embodiment, the refractive index changes along any or all radii within a sector, in which the sector has included angle φ greater than zero but less than or equal to 180 °.

In another embodiment the radius portion is in the range $0 < \Delta r \leq r_o$, and the azimuth angle φ and height z have any value provided the coordinate point (r, φ, z) is in the core region.

Further embodiments of the invention include those in which the number of sectors and the angular and radial size of the sectors are specified and the functional relationship between radius r and relative index percent Δ % is specified. Examples of the functional relationships are the α-profile, the step and rounded step index profiles, and the trapezoidal profile.

Yet further embodiments of the invention include waveguides having a segmented core and a specified number of sectors which include areas in which glass volumes of a particular size and shape have been embedded. Three and four sector embodiments having a particular core configuration and embedded portions are described below. In some embodiments, the embedded portions themselves have a segmented refractive index configuration.

In general the embodiments of this first aspect of the invention can be either single mode or multimode waveguide fibers.

A second aspect of the invention is a method of making an azimuthally and radially asymmetric waveguide fiber. The method may be employed to make either single mode or multimode waveguide fiber.

One embodiment of the method includes the steps of modifying the shape of a draw preform and then drawing the preform into a waveguide fiber having a circular cross section. The shape of the preform is thus transferred to the cylindrically symmetric features contained within the preform, specifically

the cylindrically symmetric core features. The draw preform shape may be changed by any of several methods such as etching, sawing, drilling, or grinding.

In an embodiment of the method, the preform is altered by forming holes or surface indentations therein. Subsequent drawing of the altered preform into a waveguide fiber of circular cross section causes a circularly symmetric core to become radially or azimuthally asymmetry.

In yet another embodiment of the method, two or more core preforms are fabricated and inserted into a glass tube to form a preform assembly. The waveguide fiber resulting from drawing the preform assembly has the asymmetry of the assembly. Spacer glass particles or rods may be incorporated into the tube-core preform assembly.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1a, b, & c are cross sectional views of embodiments of the novel waveguide or preform having a central core design.

Fig. 2a, b, c, & d are cross sectional views of the novel waveguide or preform having an embedded core design.

Fig. 3. is a cross sectional view of the novel waveguide or preform containing voids.

Fig. 4a & b, and 4c & d show, in cross section, the transfer of the preform outer shape to the core after drawing.

Fig. 5a & b illustrate, in cross section, the affect on the core shape of preform voids.

Fig. 6a & b, and 7a & b illustrate a cross section of a preform core and tube assembly and the resulting waveguide after drawing the assembly.

Fig. 8a & b illustrate a cross section of a notched segmented core preform and the resulting waveguide after draw.

DETAILED DESCRIPTION OF THE INVENTION

The core 2 of Fig. 1a is made azimuthally asymmetric by indentations 4. In this illustration of the novel preform or waveguide fiber, the indentations comprise the same material as that of the clad layer 6. The perpendicular sections through the core, AA' and BB', show the azimuthal variation in width of the step index profile. This particular profile is symmetric in the radial direction.

The preform or waveguide core of Fig. 1b is both radially and azimuthally asymmetric. In this illustration of the novel waveguide or preform, the core is divided into four sectors. Each of the two diagonally opposed sectors, 8 and 10 are mirror images of each other as is shown by the sections AA' and BB' taken through the core. The radial dependence of the AA' profile 16 can be a rounded step or an α-profile. The BB' profile 18 is a step index profile. The clad portions 12 and 14 may comprise any material having a refractive index lower than that of the adjacent core region. That is, the composition of the clad layer is generally limited only by the condition that the core clad structure guide rather than radiate light launched into the waveguide.

Fig. 1c is an example of a more complex structure in accord with the novel preform and waveguide. In this illustration waveguide core or core preform 20 comprises a segmented core having central region 22, and adjoining annular regions 28, 24, and 26. Each region is characterized by a respective relative refractive index Δ %, an index profile and an area determined by radii 32, 34, 36, 38 and 40. For example, central region 22 and annular region 24 may comprise respective germanium doped silica glasses and annular regions 28 and 26 may comprise silica and the relative sizes of the areas may be as shown. The asymmetry is introduced into the core preform by embedded glass volumes 30, which in general have a refractive index different from that of either annular segment 24 or 26 contacted by the glass volumes 30.

The glass volumes 30 can be formed by sawing or grinding, for example, followed by filling of the volumes with a glass by any of a number of means including deposition. The distribution of light energy carried by core 20 will be determined by the relative refractive indexes and sizes of the segments

22, 28, 24, 26, and 30. The functional properties of the waveguide are determined by the distribution of light energy across the core preform or core 20.

In another embodiment of the novel preform or waveguide, the core is comprised of a matrix glass 50 having embedded glass volumes 42, 44, and 48 as illustrated in Fig. 2a. The glass volumes extent from end to end of the preform or the waveguide drawn from the preform. The clad glass layer 52 surrounds the core 50. The refractive index of core glass 50 is higher than that of clad layer 52. Section AA' through one of the embedded volumes shows the index profile is a step profile. The sizes of cross sectional area of the embedded glass volumes can be the same or different and a number of relative orientations relative to the clad glass layer are possible. N.P.

The structure of Fig. 2a can made by drilling a preform, smoothing the walls of the resulting holes, and filling the holes with glass powder or rods. As an alternative, the core can be formed of rods which are then inserted into a holding tube, either with or without the use of spacer glass rods or particles. The need for a holding tube can be eliminated by welding the rods together using appropriate glass spacer material. The overclad layer can be deposited over the welded assembly of rods or can be fabricated as a tube which is ~~shrink~~ Shrunk onto the assembly before or during draw.

Another embodiment which includes a matrix glass and a plurality of embedded glass volumes is shown in Fig. ~~2b~~ 2c. Here the gross structure of waveguide 54 is similar to that of Fig. 2a, except that the embedded glass volumes 56, 58 and 60 each have a segmented core refractive index profile. An example of the segmented core profile is shown in the AA' cut through one of the embedded volumes in which a central region of relatively high Δ % is surrounded by two annular regions. In the illustration, the first annulus 62 is lower in Δ % than the second annulus 64. It is understood that each of the segments may a radial dependence selected from a plurality of possibilities, such as an α-profile or a rounded step profile, and the relative Δ %'s of the segments can be adjusted to provide different waveguide functional properties. N.P.

The methods of making the preform or waveguide of Fig. 2b are essentially identical to the method of making the preform or waveguide of Fig. 2a.

Two additional embodiments of this preform or waveguide type are illustrated in Figs. ~~2c~~ 2E & ~~2d~~ 2F. The embedded glass volumes 66, 68, and 70 in Fig. ~~2c~~ 2E have a rectangular cross section and are arranged substantially at the apexes of an equilateral triangle. Other arrangements of the embedded glass volumes are contemplated such as arrangement along a diameter of the core 72 pts to triangle region. The core region 72 can comprise a number of shapes and compositions. In the simple example illustrated in Fig. ~~2c~~, the core glass 72 is a step index profile and, as is required to guide light, has a higher refractive index than at least a portion of the clad layer 74.

In Fig. ~~2d~~ 2F a configuration comprising five embedded glass volumes is illustrated. Here, four glass volumes of diamond cross section 76, 78, 80 and 82 are symmetrically arranged about a circular central core region 84. It is evident that numerous variations of this design are possible. For example the refractive indexes of the embedded volumes 76, 78, 80, 82, and 84 can each have a different relative index as compared to that of the core 86.

As is shown in Fig. 3, the embedded volumes 88 in a preform or a waveguide can be voids. A waveguide having elongated voids along the long axis can be made by forming elongated voids, for example, by drilling or etching, in a core or draw preform. The index of the core glass 90 is necessarily different from that of the voids, thus providing an asymmetrical core region. In the case in which Fig. 3 represents a draw preform, the voids may be collapsed during the draw process to produce an asymmetric core. The shape of the core region after collapse of the voids is determined by the relative viscosity of core material 90 and clad layer material 92. Control of the relative viscosity of the glasses is maintained by control of temperature gradient in the portion of the preform being drawn. The relative viscosity also depends upon core and clad glass composition.

Figs. 4a and 4b illustrate the transfer of a preform shape, 98 in Fig. 4a, from the clad layer portion 94 of the preform, to the core portion 102 in Fig. 4b of a waveguide 100 drawn from preform 98. The transfer occurs as shown in Figs. 4a and 4b when the initial symmetry of the preform core 96 is the same as the symmetry of the waveguide clad layer 104. Cylindrical symmetry is shown because this is the symmetry most compatible with current preform fabrication and draw processes. Other symmetries are possible, for example, by partial transfer of the preform shape to the waveguide core shape. i.e., the final shape of the waveguide departs from cylindrical symmetry.

A cross section of a segmented core preform having a square shape is shown in Fig. 4c. After heating and drawing the preform into a cylindrical waveguide, the segmented core, 106 in Fig. 4d, takes on square shape due to the viscous flow of the core material which takes place to accommodate the cylindrically shaped surface of the clad layer.

In an analogous manner, the preform of Fig. 5a, having core 110, clad layer 112 and elongated voids 108, will produce an asymmetric core when drawn into a cylindrically shaped waveguide. However, in this case the preform is cylindrical, and the movement of the core material is due to the filling of the voids during draw. As long as the preform shape is preserved as the preform is drawn into a waveguide, the core must distort, i.e., become asymmetric, to fill the voids.

Example

A preform of the type shown in Fig. 5a was made using the outside vapor deposition process. The core region 110 was germanium doped silica and the clad layer 112 was silica. Voids 108 were formed in the preform by drilling followed by smoothing of the walls of the void using an etching solution. The preform was drawn into a waveguide fiber having the zero dispersion wavelength in the 1500 nm operation window, i.e., the waveguide was dispersion shifted. The waveguide had an unusually large mode field diameter of 10.4 μm as compared to mode field diameters in the range of 7 μm to 8 μm for dispersion shifted waveguides having an azimuthally symmetric core.

A method of making an asymmetric core is illustrated in Figs. 6a and 6b. Segmented core preforms 114, 116 and 118 are fabricated using any of several known methods including, outside vapor deposition, axial vapor deposition, plasma deposition, or modified chemical vapor deposition. The core preforms are inserted into tube 122 where they are held in place by spacer rods 120. The rods may be made of silica, doped silica or the like. If needed, a clad layer 124 may be deposited on the tube. The preform assembly may now be drawn into a waveguide fiber having cores 130, 132, and 134 embedded in core glass 128 and surrounded by clad glass layer 126 as shown in Fig. 6b. The assembly as shown in Fig. 6a may be drawn directly. As an alternative, the deposited clad layer may be consolidated prior to draw. In addition, before clad deposition, the tube, core preform and spacer rod assembly may be heated sufficiently to soften the surfaces thereof to cause them to adhere to each other, thereby forming a more stable structure for use in the overclad or draw process.

The method of making an asymmetric core shown in Figs. 7a and 7b is closely related to that illustrated in Figs. 6a and 6b. In Fig. 7a the core is bounded by annulus 136 which serves to better contain light propagating in step index core preforms 138, 140, and 142. As described above, spacer rods or glass powder may be used to stabilize the relative positions of the core preforms within the annulus. The assembly of core preforms, optional spacer material, annulus and overclad material may be drawn directly or first consolidated and then drawn. The resulting waveguide fiber is shown in Fig. 7b.

A final example of a method of forming an asymmetric core is shown in Figs. 8a and 8b. In Fig. 8a a preform has a segmented core having central region 144, first annular region 146, and second annular region 148. The preform has been ground or sawed or the like to form notches 152. The notches may be empty or filled with material 150 which is a material different in composition from that of clad layer 154. The preform assembly is drawn to form a waveguide having an asymmetric core as shown in Fig. 8b. Here again

the assembly may be drawn directly or deposition, consolidation, or tacking steps may be carried out before draw to hold the parts of the preform in proper relative registration.

Although particular embodiments of the invention have been disclosed and described herein, the invention is nonetheless limited only by the following claims.